A Modelica-based Virtual Testbed for Hybrid-Cooled Data Centers

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Atlanta, GA, USA



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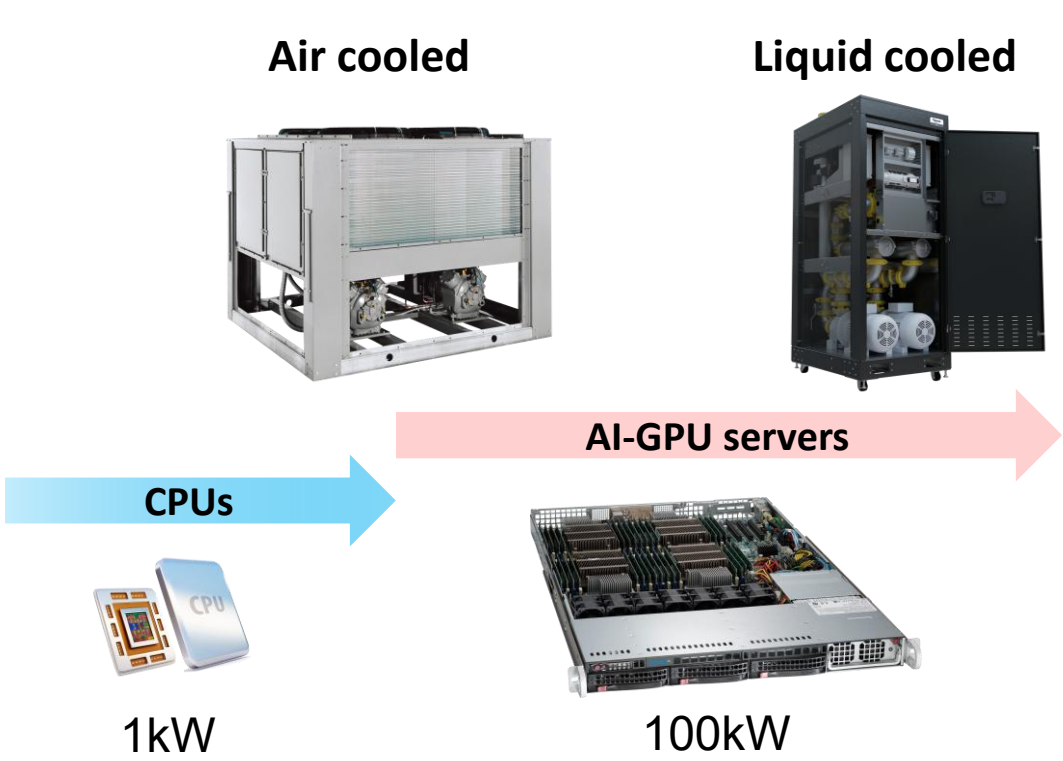


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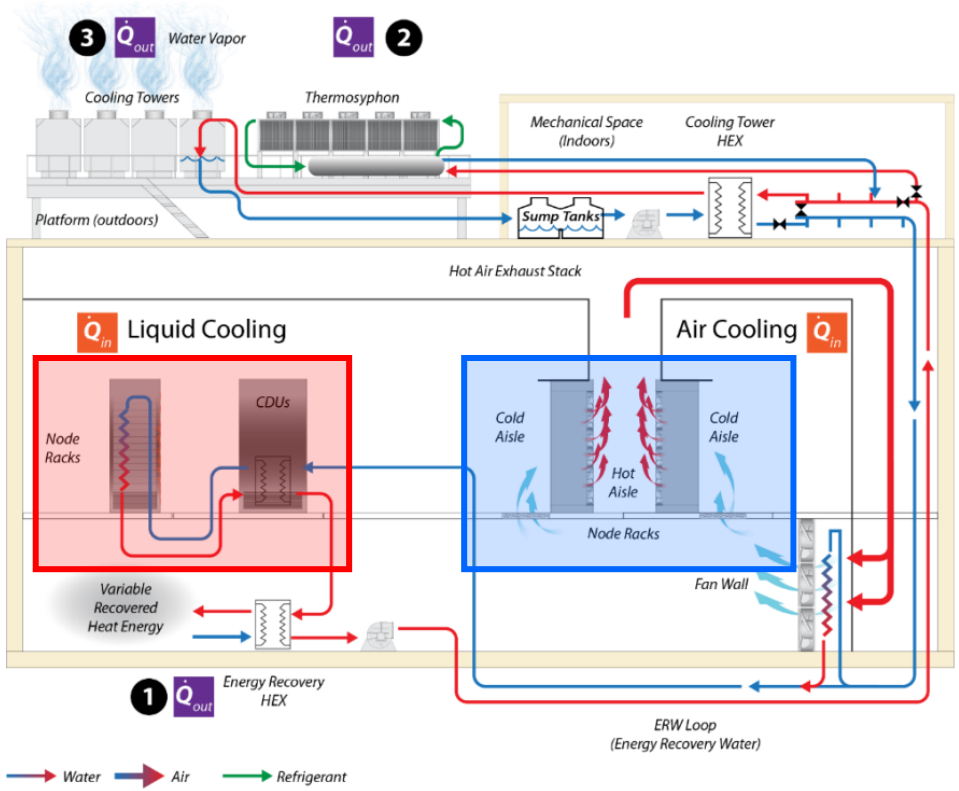
Introduction

AI-driven computing is pushing data centers from air cooling toward liquid cooling.

While large facilities increasingly rely on hybrid cooling systems.



From air cooled to liquid cooled



Data center at NLR

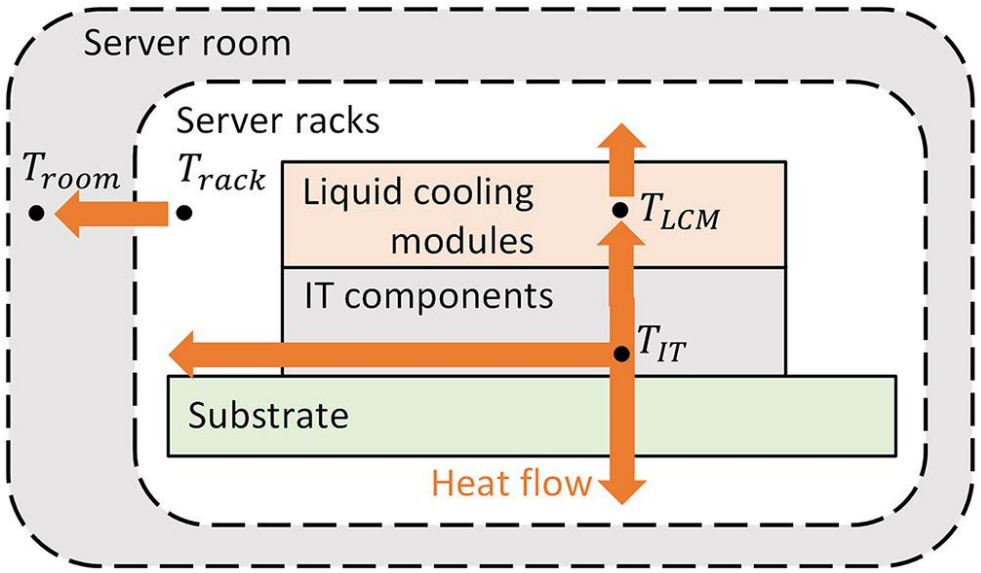
Source: David, et al.

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State-of-the-Art and Opportunity

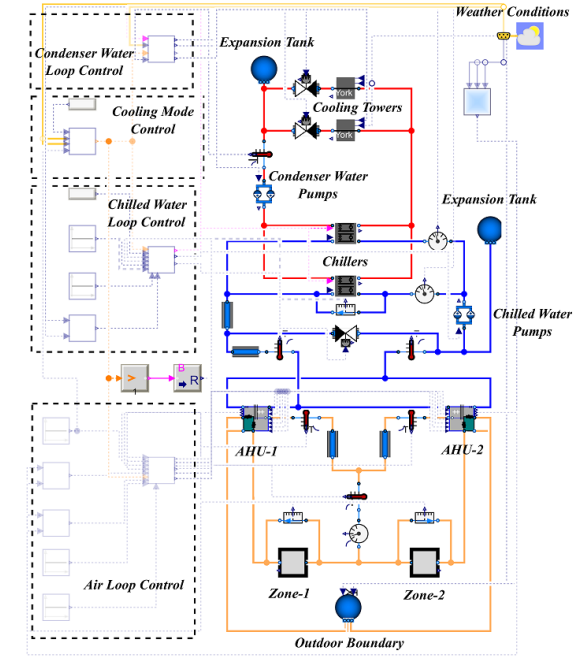
Existing studies are increasingly addressing hybrid cooling through experiments and heat-transfer analysis.

Modelica provides an effective platform for capturing the dynamic behavior of these complex coupled systems.



The heat transfer process from IT equipment to the server room environment

Source: Gheni, et al.



Modelica model for Data Center Cooling

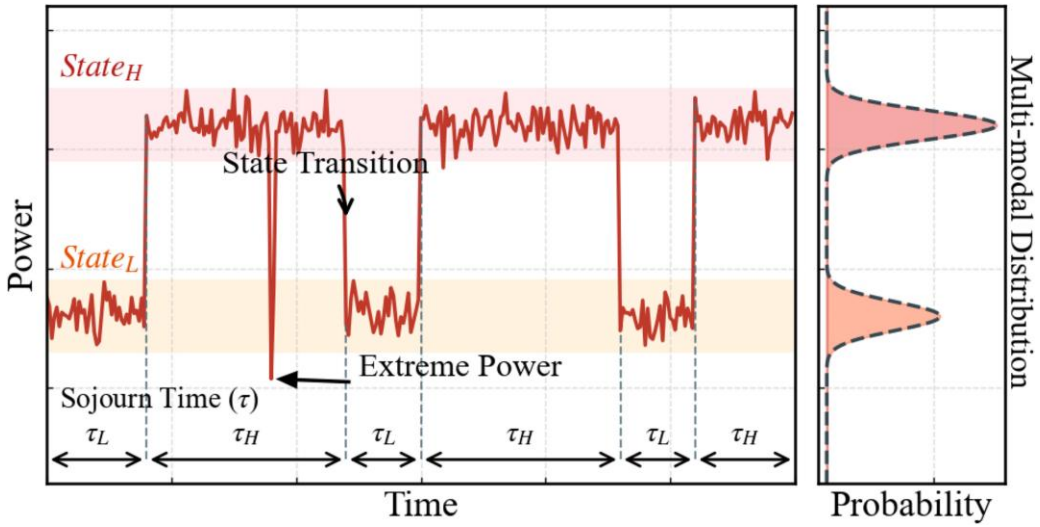
Source: Fu, et al.

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Thermal Response in Hybride-Cooled Data Center

Thermal response

- Assess how the Modelica models captures **thermal behavior** of AI data-center

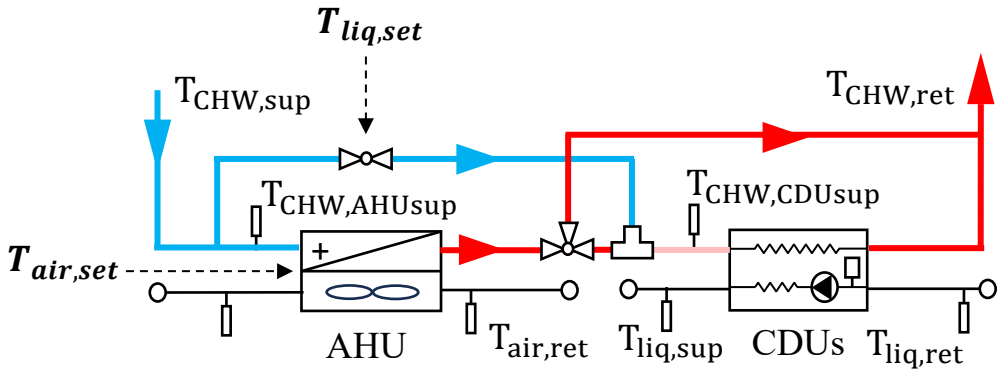


Schematic diagram of AI workload power characteristics

Source: Xie, et al.

Setpoint Coordination

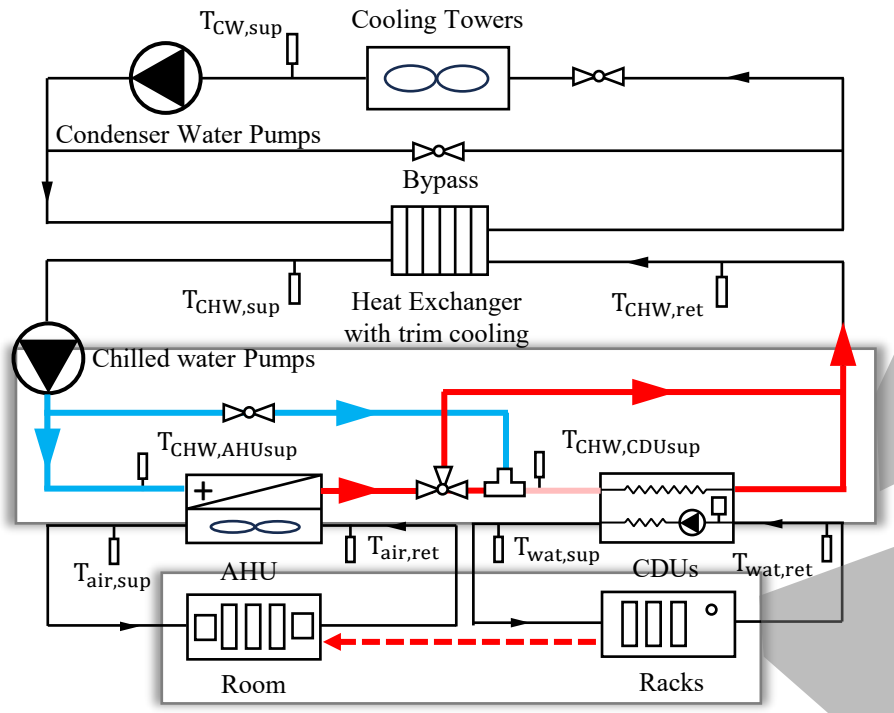
- Evaluate how coordinated air-side and liquid-side cooling setpoint optimization can reduce **cooling energy** consumption



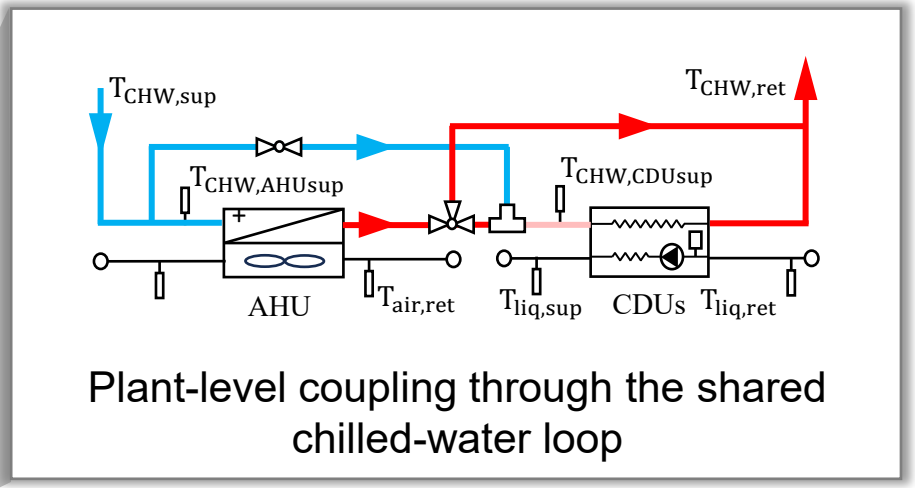
Plant-level coupling through the shared chilled-water loop

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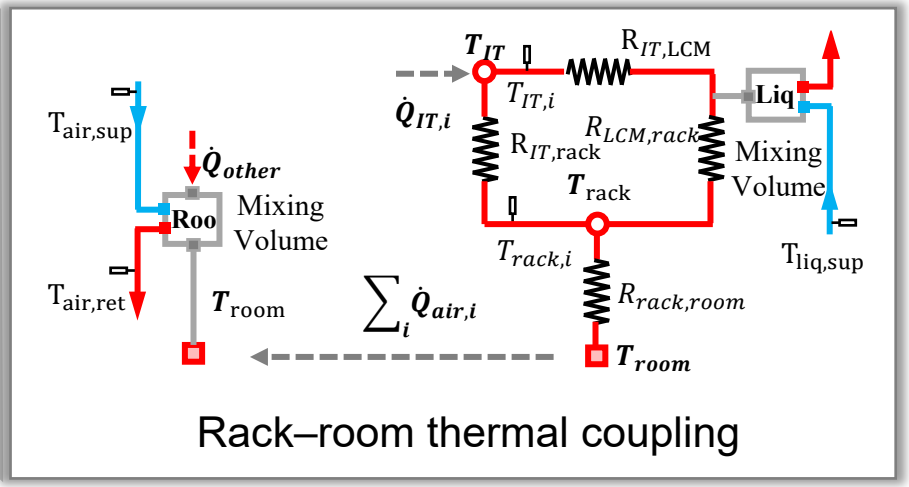
Thermal Coupling in the Hybrid-Cooled Data Center Model



Schematic of the hybrid cooling system



Plant-level coupling through the shared chilled-water loop



Rack–room thermal coupling

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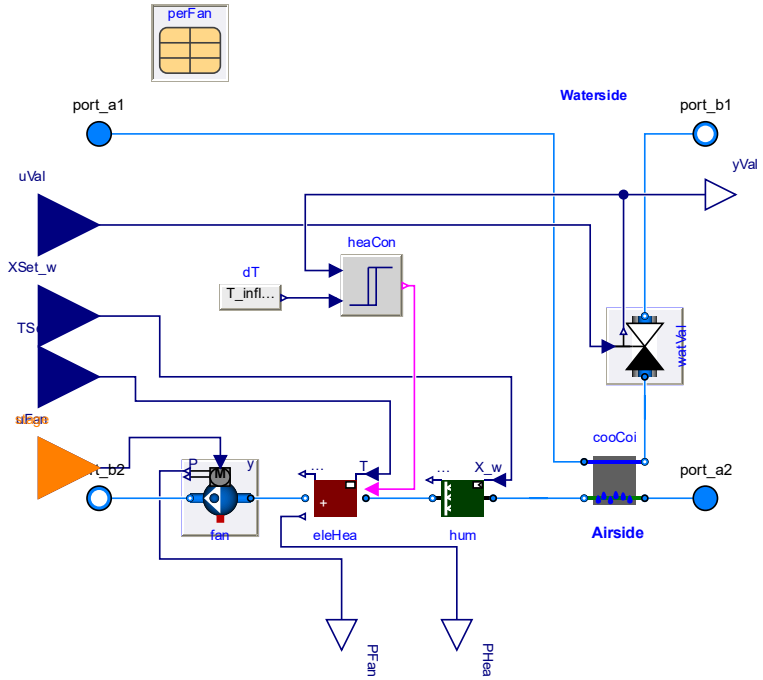
Key Equipment from the Buildings Library

Uses

Modelica Buildings 12.1.0
Modelica Standard 4.0.0

CoolingCoilHumidifyingHeating

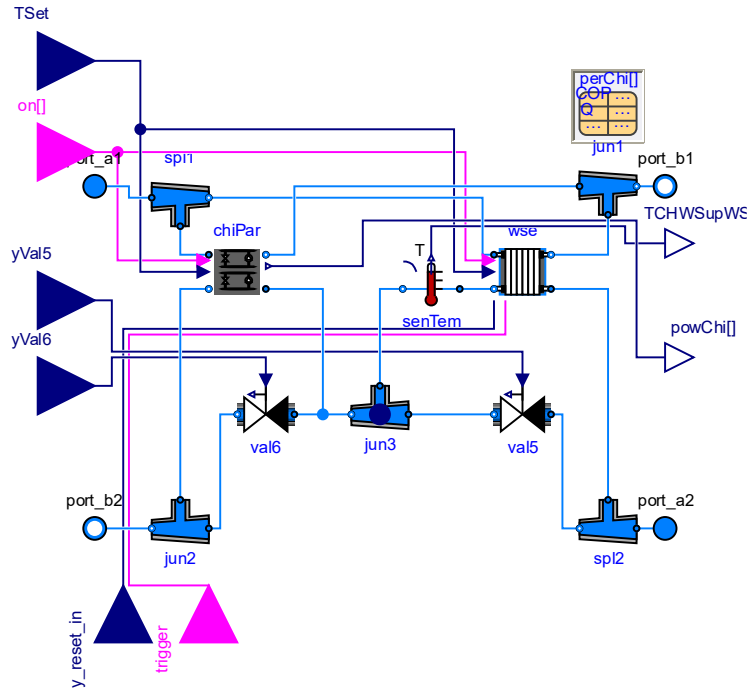
- Instance of Buildings.Applications.DataCenters.AHUs.Example.AirHandlingUnitControl
- Represent a typical air handler with a cooling coil, a variable-speed fan, a humidifier and an electric reheater.



IntegratedPrimaryPlantSide

Source: Wetter, et al.

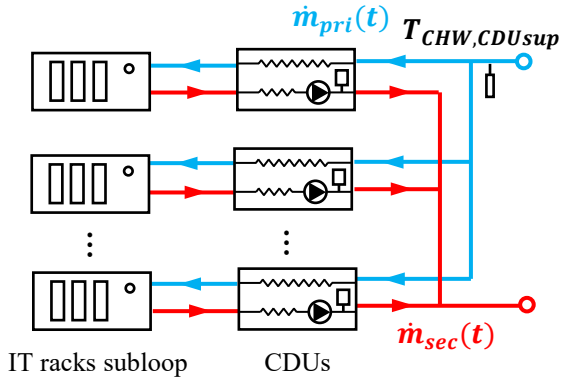
- Instance of Buildings.Applications.DataCenters.ChillerCooled.Equipment
- Integrated water-side economizer (WSE) on the plant side of the primary-only chilled water system

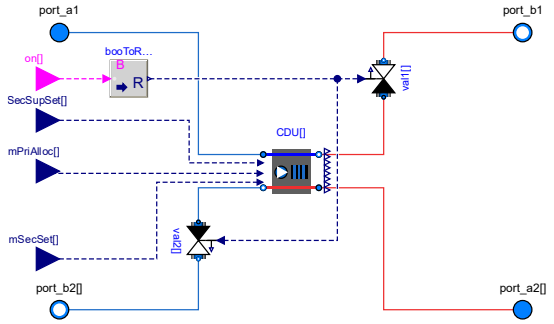


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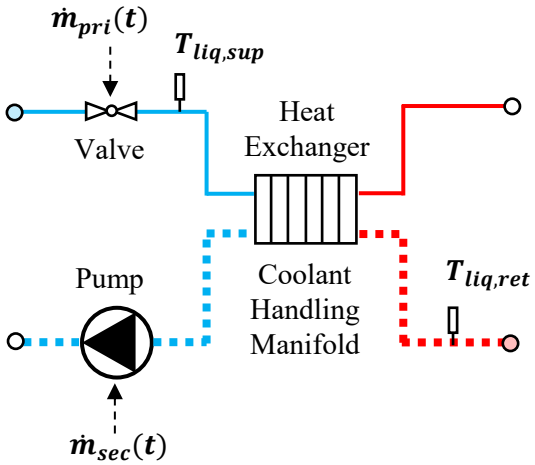
Equipment in the Hybrid DC

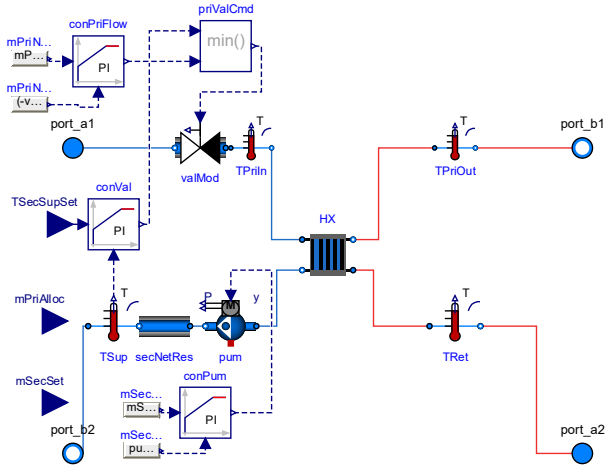
(a) The parallel CDU system



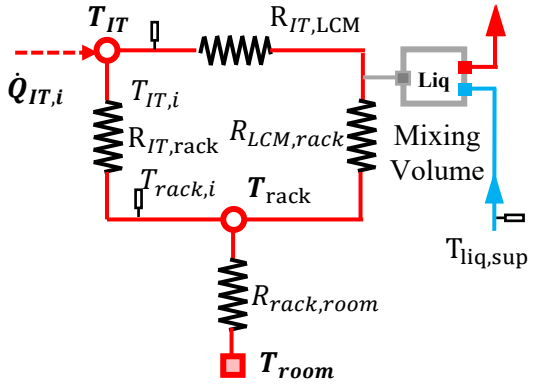


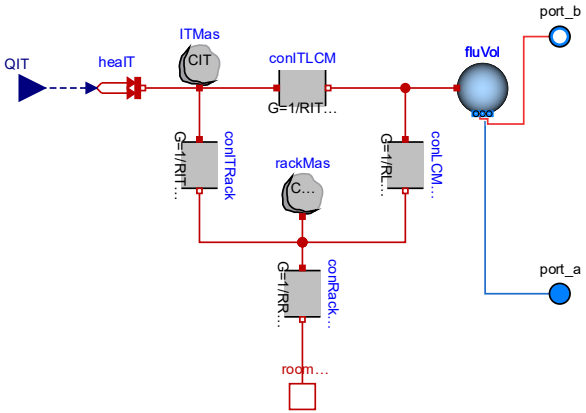
(b) A single CDU





(c) The single-rack thermal model

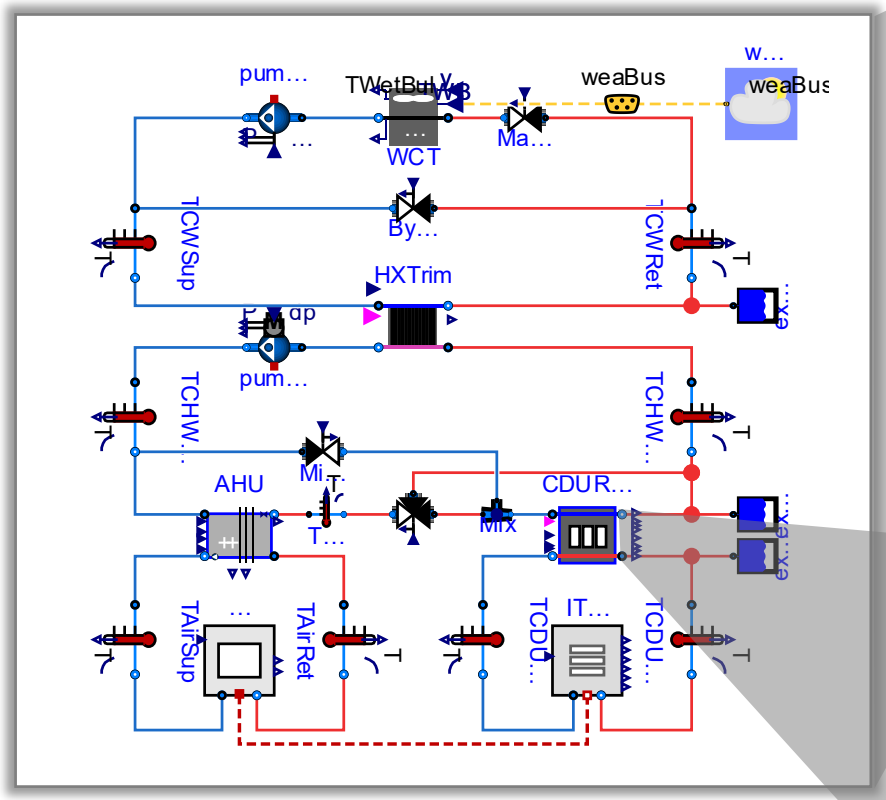




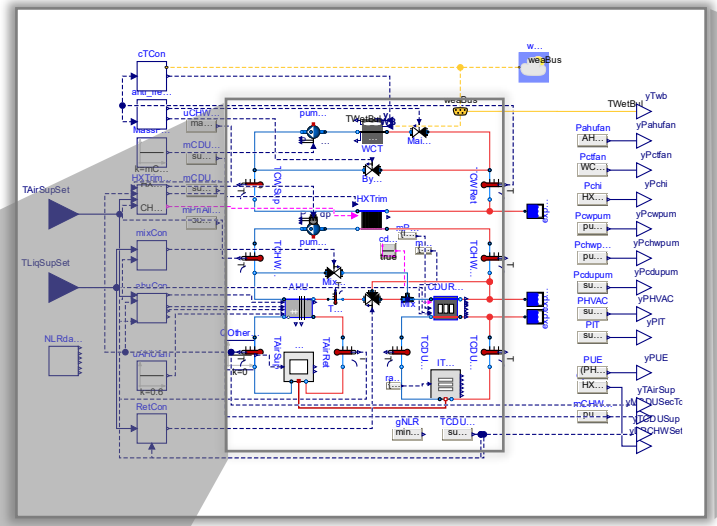
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Modelica Implementation

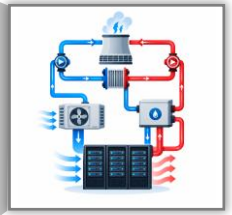
Hybrid cooling system



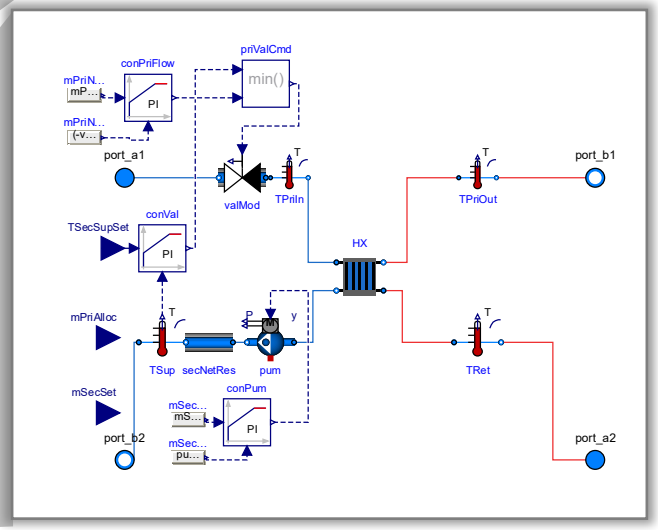
Top-Level FMU



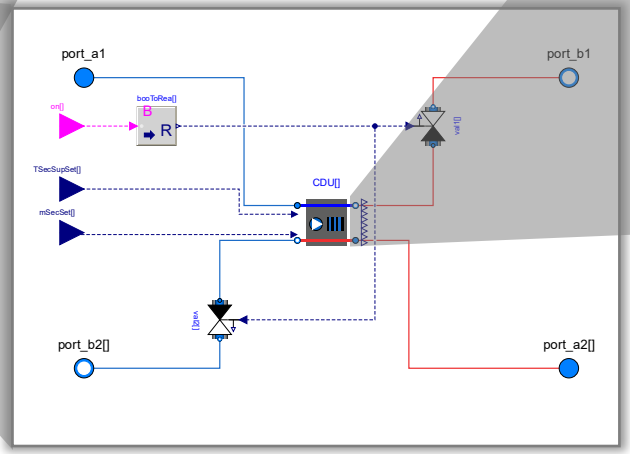
Hybrid DC



Single CDU



Parallel CDU system



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Validation

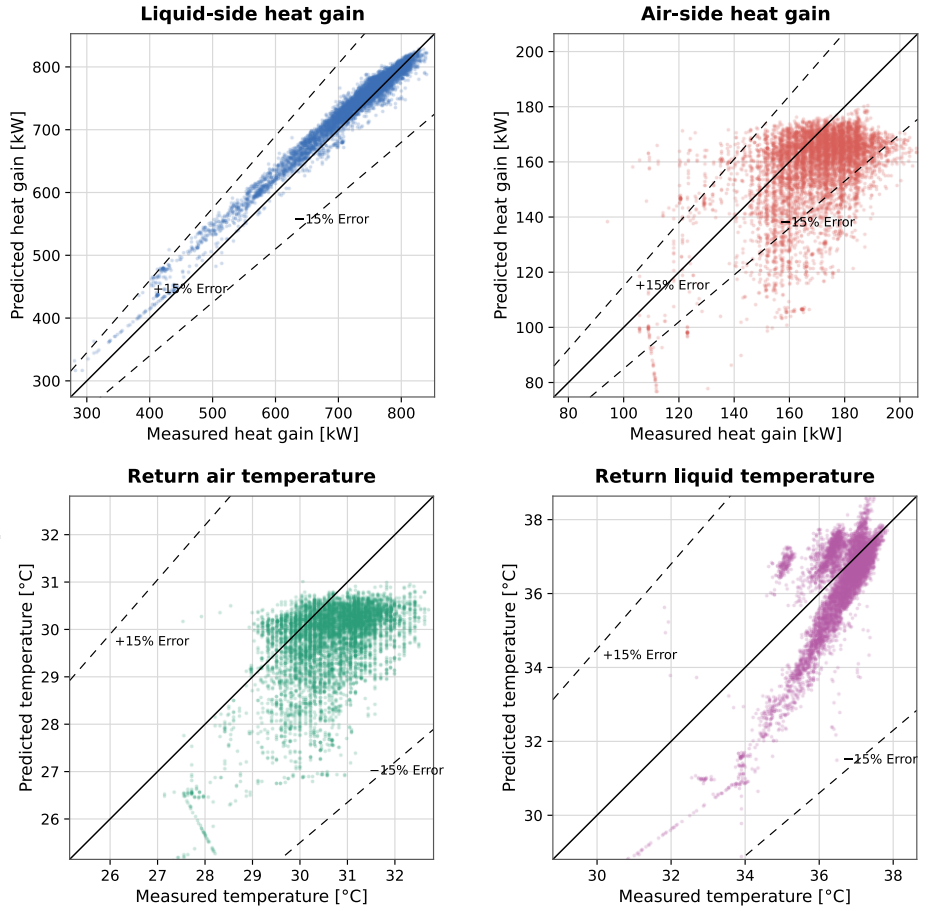
The Modelica testbed is validated against **measured data** using normalized mean bias error (NMBE) and coefficient of variation of the root mean square error (CVRMSE).

$$\mathrm{NMBE} = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{n\bar{y}} \times 100\%$$

$$\mathrm{CVRMSE} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}}{\bar{y}} \times 100\%$$

Performance metrics of the virtual testbed on the minute-level validation dataset. Source: Sickinger, et al.

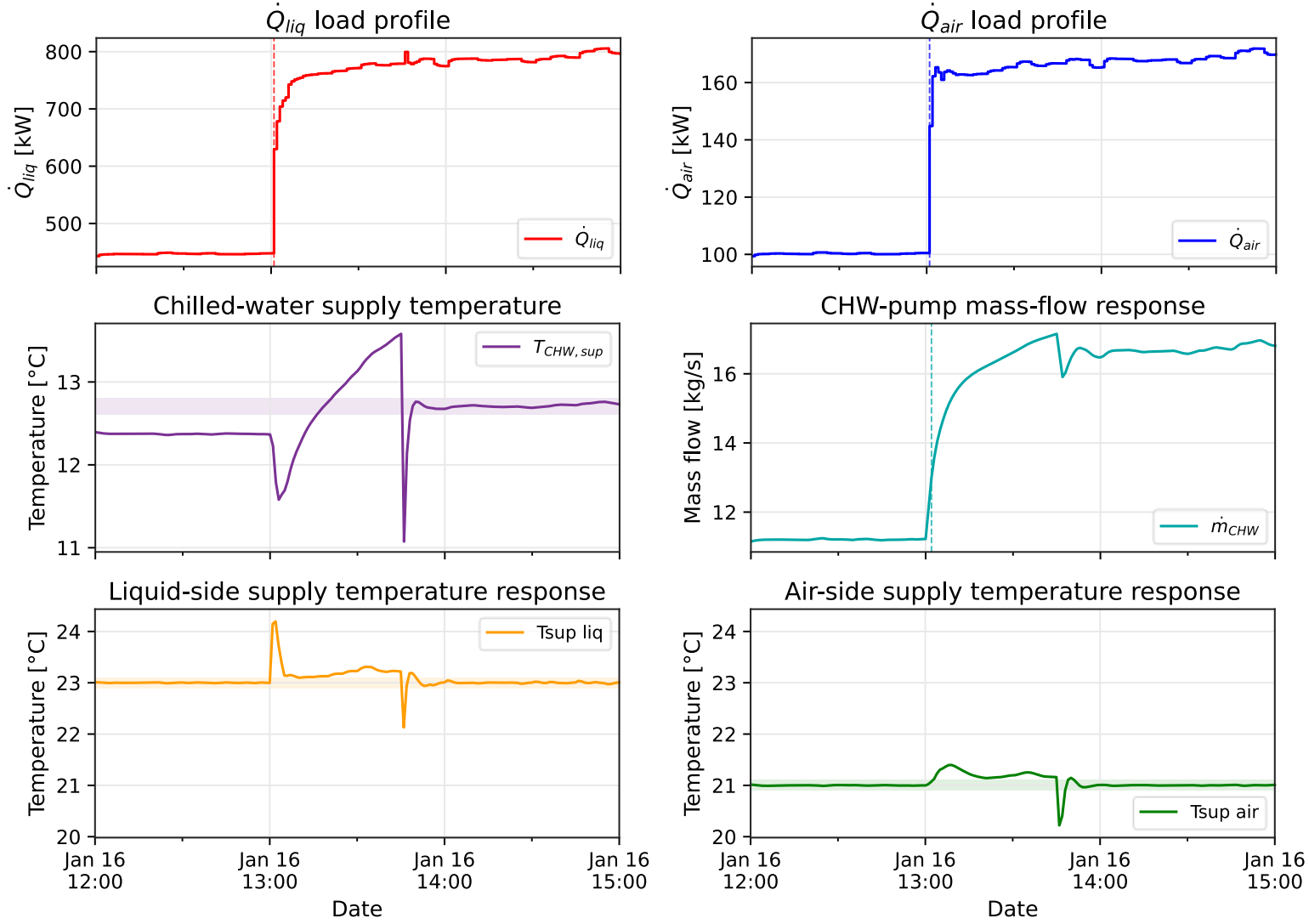
Variable	NMBE	CVRMSE
Liquid-side heat gain	-1.61%	2.60%
Air-side heat gain	6.86%	10.98%
Return air temperature	2.85%	3.83%
Return liquid temperature	0.83%	2.53%

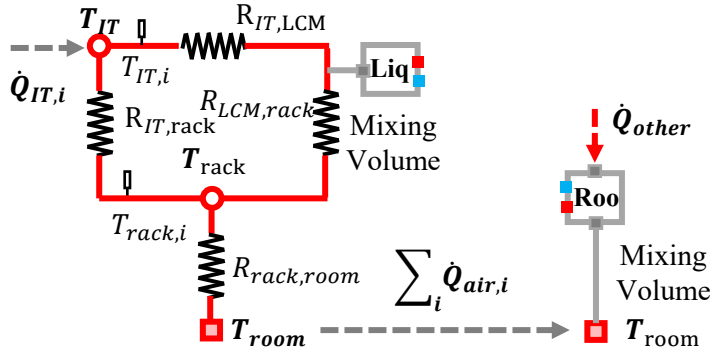


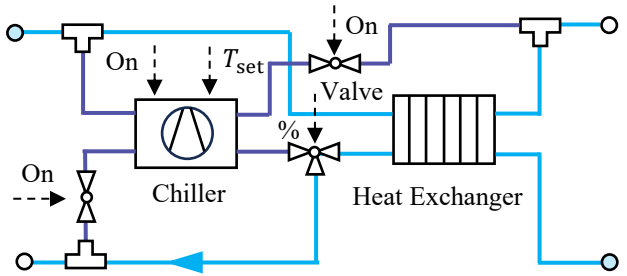
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Thermal Response at Distinct Ramp-up







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Coordinated Setpoint Optimization via Grid Search

Objective: Minimize cooling energy by coordinating air-side and liquid-side supply-temperature setpoints while satisfying thermal constraints

Source: Ensor, et al.

Candidate grid: $\mathcal{G} = \mathcal{G}_{air} \times \mathcal{G}_{liq}$

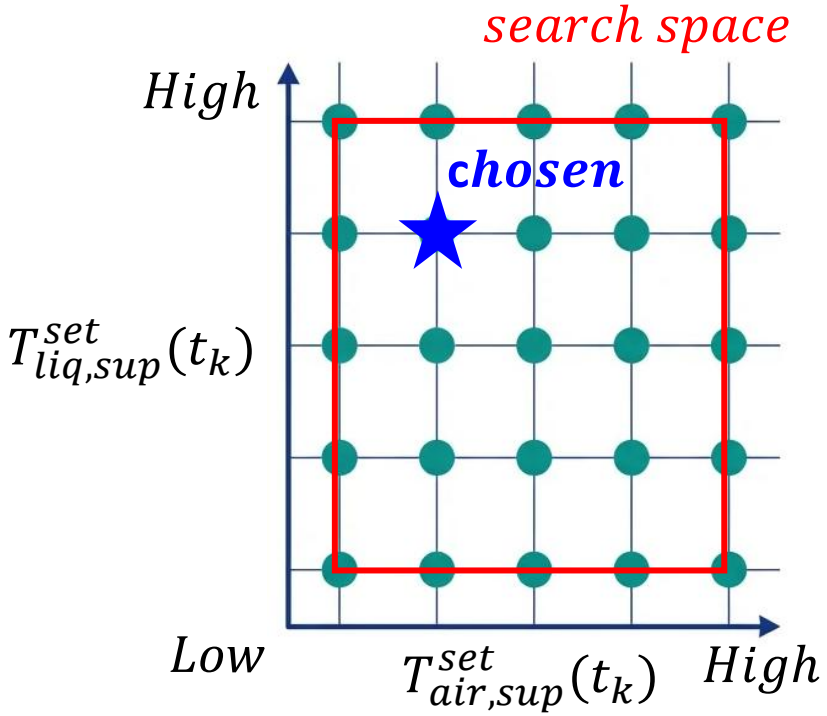
Decision vector: $\boldsymbol{x}_k = \begin{bmatrix} T^{set}_{air,sup}(k) \\ T^{set}_{liq,sup}(k) \end{bmatrix} \in \mathcal{G}$

Objective: $\boldsymbol{x}^*_k = arg\min_{\boldsymbol{x}_k \in \mathcal{G}} E_k(\boldsymbol{x}_k)$

Thermal constraints:

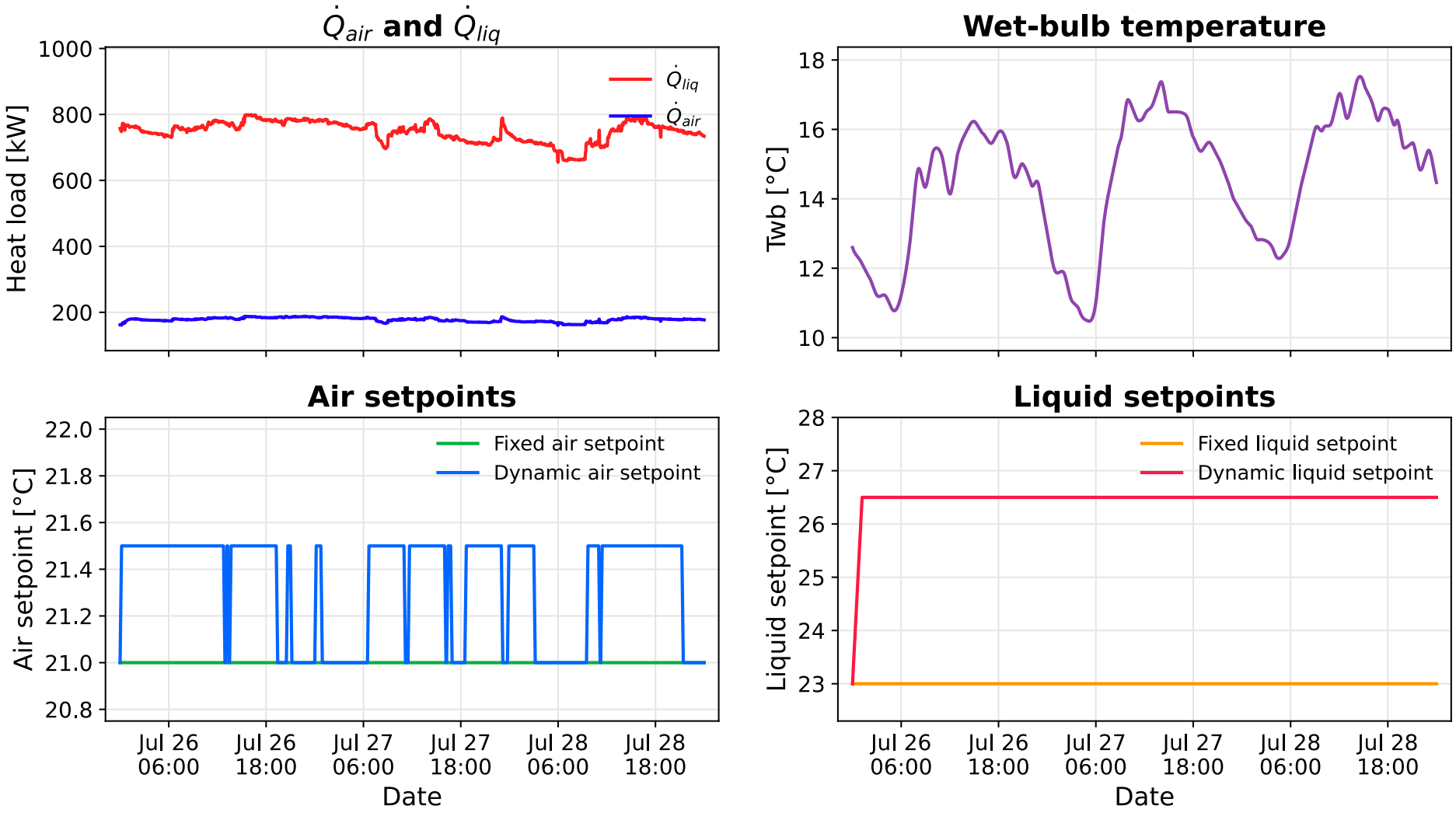
$$T_{air,in,i}(\tau) \leq T^{max}_{air,in}, \tau \in [t_k, t_k + \Delta t]$$

$$T_{liq,in,i}(\tau) \leq T^{max}_{liq,in}, \tau \in [t_k, t_k + \Delta t]$$



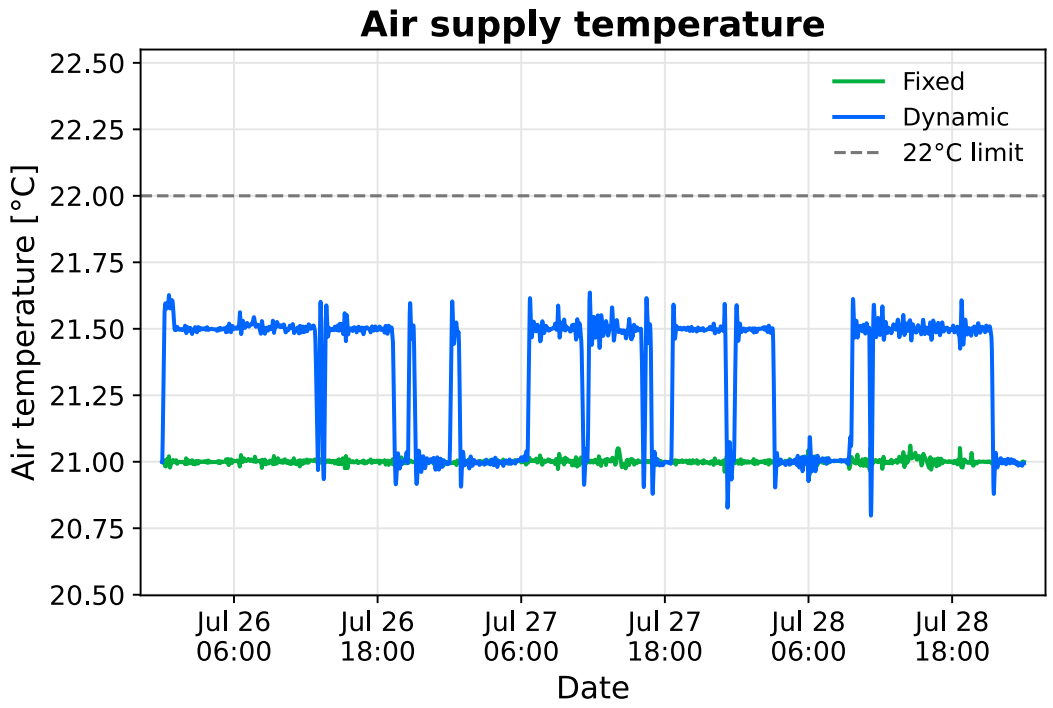
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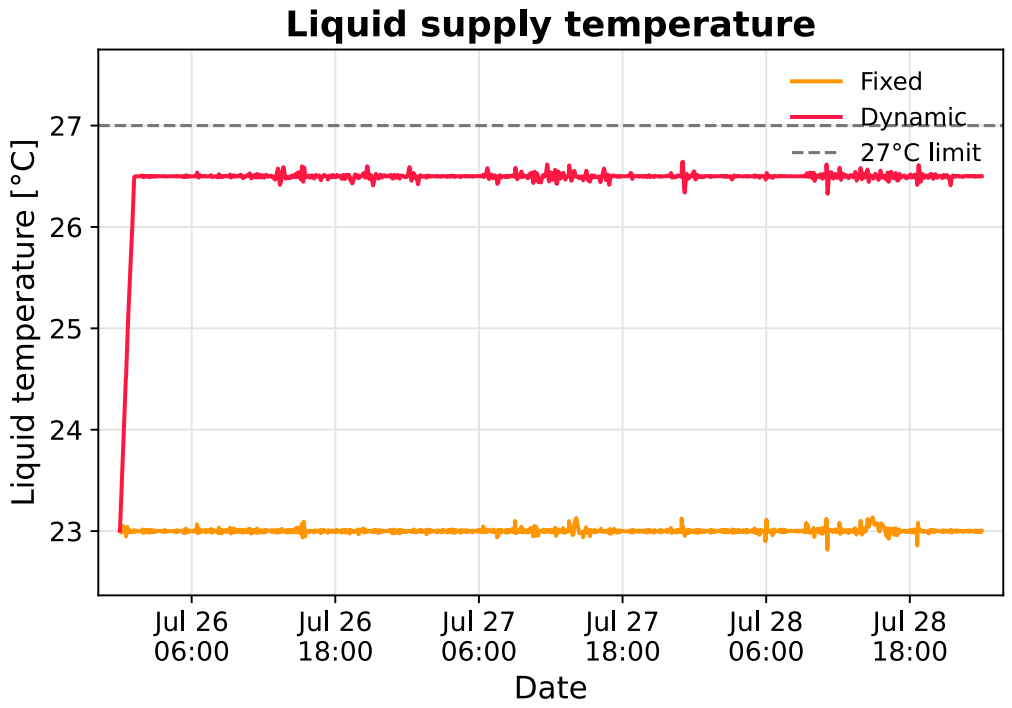
Optimized Setpoints



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Thermal Behavior



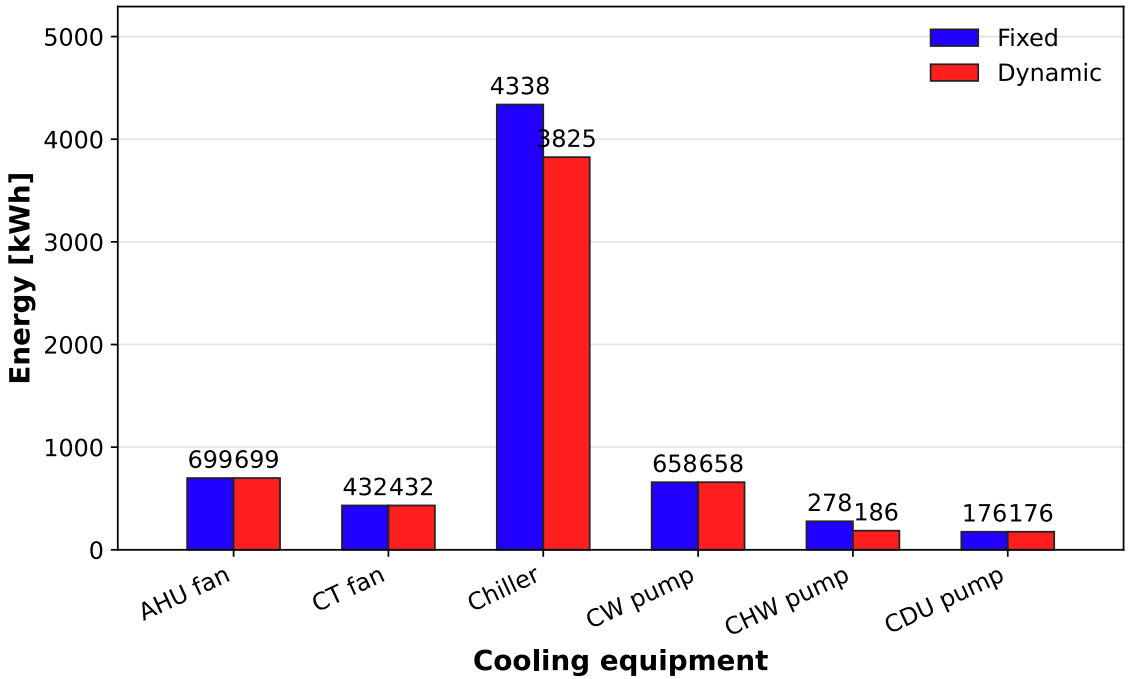


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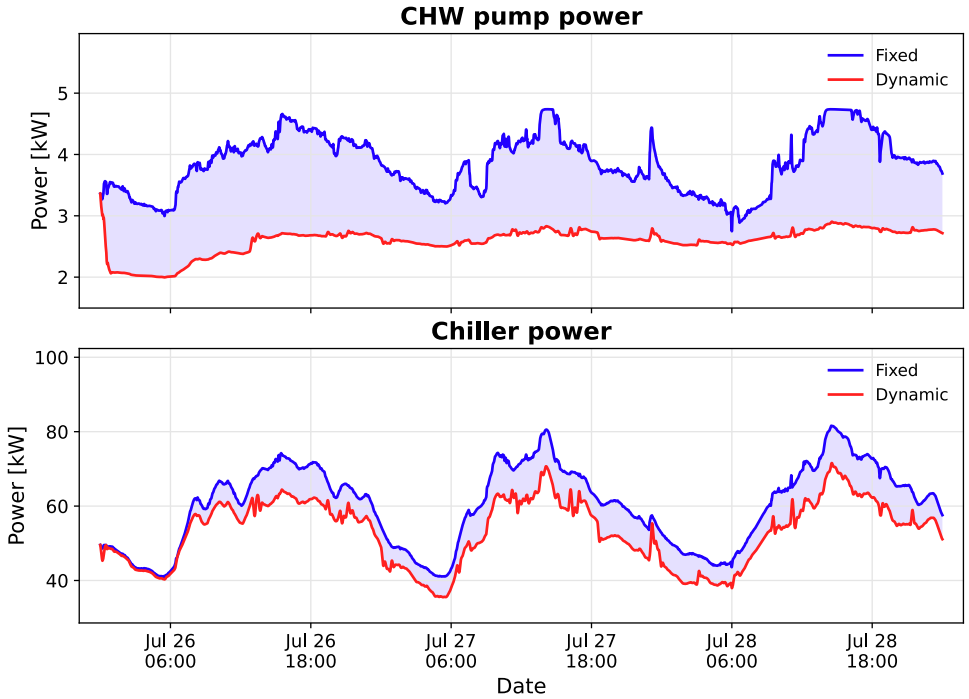
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Energy Savings and Power Profile

Dynamic setpoint optimization reduces total cooling energy use by 9.2% over the three hottest days, with the largest savings from the chiller.



Equipment-level cooling energy breakdown under fixed and dynamic setpoint control (Jul 26-28, 2017)



Power Profiles under Fixed and Dynamic Control (Jul 26-28, 2017)

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Conclusions

- Developed a Modelica model for a **hybrid-cooled data center**.
- Enabled advanced control studies under **rapid IT load** ramp-up events.
- Demonstrated that accounting for distinct air-side and liquid-side dynamics can reduce cooling energy use by **9.2%** over the three hottest days.

Acknowledgements



U.S. National Science Foundation
ECCS-2446782



[1] University Graduate Fellowship
[2] ICDS Rising Researcher

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Reference

[1] Gheni, Mashhur, Henner Kerskes, and Konstantinos Stergiaropoulos. "Operational analysis of the cooling system in a direct liquid-cooled data center: a measurement and simulation study on the impact of supply water temperature." Applied Energy 403 (2026): 127061.

[2] Fu, Yangyang, et al. "Equation-based object-oriented modeling and simulation for data center cooling: A case study." Energy and Buildings 186 (2019): 108-125.

[3] Sickinger, David E., et al. Thermosyphon cooler hybrid system for water Savings in an Energy-Efficient HPC data center: Results from 24 months and the impact on water usage effectiveness. No. NREL/TP--2C00-72196. National Renewable Energy Laboratory (NREL), Golden, CO (United States), 2018.

[4] Ensor, Katherine Bennett, and Peter W. Glynn. "Stochastic optimization via grid search." Lectures in Applied Mathematics-American Mathematical Society 33 (1997): 89-100.

[5] Xie, Xin, et al. "Risk-aware coordinated scheduling of battery storage and AI data centers with decoupled multi-layer AI workload models." Applied Energy 427 (2027): 128836.

[6] Wetter, Michael, et al. "Modelica buildings library." Journal of Building Performance Simulation 7.4 (2014): 253-270.

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